REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
		FINAL 15 May 93 To 14 May 96

4. TITLE AND SUBTITLE

RETRIEVAL AND STORAGE CONSEQUENCES OF WORKING MEMORY LIMITATIONS

5. FUNDING NUMBERS

F49620-93-1-0336
61102F
2313/BS

6. AUTHOR(S)

Dr Randall W. Engle

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Dept of Psychology
University of South Carolina
Columbia SC 29208

8. PERFORMING ORGANIZATION REPORT NUMBER

AFOSR TR-96-0421

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

AFOSR/NL
110 Duncan Ave Room B115
Bolling AFB DC 20332-8080

Dr John F. Tangney

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

19960813 166

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release;
distribution unlimited.

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The research funded by this grant addressed questions about the nature of individual differences in working memory (WM) capacity. Experiments showed that high and low WM subjects did not differ in retrieval from the inactive portion of memory and differed in retrieval from active or primary memory only under conditions of conflict or interference. In neither case was there a set size effect in retrieval from secondary memory. Another set of experiments showed that suppression of distracting or interfering information was a function of WM capacity and that suppression was diminished if the subjects was operating under a memtal work load. The final project completed on the grant was a large scale factor analysis to determine whether the wide range of putative WM tasks reflect a common mechanism, whether that mechanism is manifest in simple short-term memory tasks and the relationship of these constructs to general fluid intelligence. In a series of confirmatory factor analyses, the WM tasks loaded closely together and a separate STM factor was necessary. The WM factor was closely associated with a factor for general fluid intelligence. This research led to the conclusion that the dimension called WM capacity reflects stable individual differences in the ability to bring controlled, effortful attention to bear on novel tasks, tasks that require an individual to closely monitor his or her own behavior, tasks that require that information be maintained over time for later use and tasks that require that information be suppressed to prevent distraction and interference.

14. SUBJECT TERMS	15. NUMBER OF PAGES
DTIC QUALITY INSPECTED 4	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
(U)	(U)	(U)	(U)

Abstract

The research funded by this grant addressed questions about the nature of individual differences in working memory (WM) capacity. Experiments showed that high and low WM subjects did not differ in retrieval from the inactive portion of memory and differed in retrieval from active or primary memory only under conditions of conflict or interference. In neither case was there a set size effect in retrieval from secondary memory. Another set of experiments showed that suppression of distracting or interfering information was a function of WM capacity and that suppression was diminished if the subjects was operating under a mental work load. The final project completed on the grant was a large scale factor analysis to determine whether the wide range of putative WM tasks reflect a common mechanism, whether that mechanism is manifest in simple short-term memory tasks and the relationship of these constructs to general fluid intelligence. In a series of confirmatory factor analyses, the WM tasks loaded closely together and a separate STM factor was necessary. The WM factor was closely associated with a factor for general fluid intelligence. This research led to the conclusion that the dimension called WM capacity reflects stable individual differences in the ability to bring controlled, effortful attention to bear on novel tasks, tasks that require an individual to closely monitor his or her own behavior, tasks that require that information be maintained over time for later use and tasks that require that information be suppressed to prevent distraction and interference.

Final Report

Grant: ***F49620-93-1-0336***

Grantee: ***Randall W. Engle***

Title: ***Retrieval and storage consequences of working memory limitations***

Unrestricted distribution, unclassified

14 July 1996

Prepared for:

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

BOLLING AFB DC, 20332-6448

The purpose of this research was to address a proposal I referred to as general capacity theory. This view argued that the relationship between measures of working memory capacity and higher level cognitive measures such as reading comprehension does not occur because of a relationship between the processing component of the working memory task and the higher level task. General capacity theory argued that the relationship occurs because individuals vary in working memory capacity independently of the specific task being performed. According to this view, a measure of working memory should successfully transcend task dependency in its prediction of higher level cognitive functioning. As such, the memory span test could be embedded in a secondary processing task that is unrelated to any particular skills measure and still predict success in the higher level task. This view sees the individual differences in working memory as reflecting a relatively stable characteristic of the subject.

The ideas presented as general capacity theory paralleled theories proposed by Anderson (1983), Glass (1984), Schneider and Detweiler (1987) and Cowan (1988) with regard to nomothetic views of working memory, activation and resource capacity, and Just and Carpenter (1992) with regard to individual differences in working memory. I assume that working memory is much more extensive than assumed by traditional buffer theories (e.g., Waugh & Norman, 1965; Atkinson & Shiffrin, 1968). It consists of those temporary or permanent knowledge units in long-term declarative memory that are currently

active. Short-term memory is that information that is maintained within the grasp of immediate consciousness, which amounts to a threshold level of activation (Cowan, 1995).

What is the role of processing under this view? General capacity theory assumed that procedures only make demands on working memory to the extent that: (a) they are so poorly learned that a search of declarative memory is required for a production to match the contents of working memory, or (b) the procedure produces intermediate and final products which must be stored as a temporary declarative memory unit in working memory.

Individual differences on measures of working memory capacity have been shown to have good predictive validity for a wide variety of higher level, real world cognitive tasks. For example, Engle (1996) pointed out that putative measures of working memory capacity have shown significant correlations with measures of reading and listening comprehension (Daneman & Carpenter, 1980; 1983), vocabulary learning from context (Daneman & Green, 1986), learning to spell (Ormrod) , writing (Benton, 1984), following directions - both verbal and spatial (Engle, Carullo & Collins, 1991), and learning to write computer programs (Kyllonen & Stephens, 1990). In fact, Kyllonen and Christal (1990) showed that working memory capacity accounted for nearly all the variance in measures of reasoning ability and argued that working memory capacity is the mechanism underlying general intelligence.

How does general capacity theory allow for individual differences of the type described above? The theory assumes that individuals differ in the total level of activation available to their system. The amount of total activation available is an abiding characteristic of the individual's system and would not change as changes occur in the knowledge structure. Thus, an individual might develop a knowledge base that would allow the use of retrieval structures to drastically increase the amount of information stored and recalled. However, an analysis of retrieval would show a relatively small number of links at each level of the hierarchy (Ericsson and Staszewski, 1989). Broadbent (1975) and Schneider and Detweiler (1987) provide further support and argument for the view that working memory limitations are still observed even when those limitations are extended or apparently circumvented. I argued in the original grant proposal that complex working memory tasks, like those used by Daneman and Carpenter (1980) and Turner and Engle (1989), provide a more accurate measure of the amount of activation available to the individual on a moment to moment basis than do traditional STM tasks. The WM tasks all demand that the individual attend to the processing component, then to the span item, then to the processing component of the next sentence or operation and then back to the span item, and so on, until recall is required. This models the very attention-switching feature described above, and I would argue that the number of span items recalled in this context reflects the amount of

activation available for maintaining the temporary structures for retention of the span items while concomitantly switching attention back and forth to other interpolated activities.

The research questions posed in the original grant proposal are listed below and each question is followed by the research that addressed the question.

Research Questions:

(1) Is WM capacity determined by the limit on total long-term memory activation? Does working memory capacity affect speed of recognition and speed of retrieval from LTM and/or STM? General capacity theory argued that working memory capacity, as measured by the complex memory span tasks, refers to the amount of total activation available to the information processing system. As such, measures that have been presumed to reflect activation would be sensitive to individual differences in working memory.

Our earlier work (Cantor & Engle, 1993) had suggested that Hi and Lo working memory capacity subjects could differ in retrieval time from primary memory, secondary memory or both. Series 1 in the original proposal was directed at this question. A task was developed that allowed us to measure the time for the subject to retrieve an item from the active portion of memory, or primary memory, and from the inactive portion of memory, or secondary memory. Five studies were completed on this question and the results were

published in Conway and Engle (1994). I will first summarize the conclusions from those studies and then describe the procedures and results that led to those conclusions. ***Regardless of interference condition, Hi and Lo working memory capacity subjects do NOT differ in retrieval time from inactive or secondary memory. If there is no interference or response competition involved, Hi and Lo working memory capacity subjects do NOT differ in retrieval time from active or primary memory. Hi and Lo WM subjects DO differ in retrieval time from primary memory if the items being retrieved belong to more than one set which creates interference among the items.***

Subjects in 4 experiments learned sets of items in association with a cue that was a number representing the number of items (either letters or words) in the set. In Experiment, for example, a subject might learn to recall the letters B and Q in response to the cue, 2, and the letters L, W, C and R to the cue, 4, etc. In two of the four experiments (1 & 3), there were set sizes of 2, 4, 6, & 8 and letters as set items and in two of the studies (2 & 4) there were set sizes of 2, 4, 6, 8, 10 & 12 and words were used as set items. In two of the studies (3 & 4) there was no overlap in set membership so that each letter or word was in one and only one set. In the other studies (1 & 2) each item was a member of 2 different sets.

After the sets were learned to a criterion of 3 perfect recalls for each set, there was a speeded recognition task. On each trial, the subject was presented

with a number representing a set (e.g., 8) and an item. The subject was to press a Yes or No key as rapidly as possible (while maintaining accuracy) as to whether the item was a member of the set being cued, in this instance, set size 8. To distinguish between active and inactive memory, on half the trials the set cue occurred alone for 1 second after which the item appeared and the reaction time was measured from the onset of the item. These trials were assumed to measure retrieval time from active or primary memory. A pilot study had shown that 1 second was more than enough time for subjects to retrieve the entire set into active memory. Thus, we felt safe in assuming that 1 second was a sufficient lead time for the subject to encode the set cue and make the set information available in active memory. We assumed that, on these trials, when the item appeared the subject would need only to search the items in the previously activated set so the measure was a valid measure of retrieval time from primary memory. On the other half the trials, the set cue and the item appeared at the same time for a 0 delay. We assumed that, on these trials, the subject must first bring the set information into active memory and then search the items in the activated set. Thus, these trials represented both the time to retrieve set information into active memory and the time to search primary or active memory. Retrieval from primary memory could be estimated by the reaction time on the 1 second delay trials. Retrieval from inactive or

secondary memory could be estimated by the difference between the 1 second delay trials and the 0 second delay trials.

The results of Experiments 1 & 2 most closely resemble those in Panel C. If there was overlap in set membership, as there was in Exps. 1 & 2, the difference between the set size function for delay 1 and delay 0 was not different for Hi and Lo span subjects. That is, Hi and Lo span subjects took the same amount of time to bring the set information into active memory. They did, however, differ in the time to search the contents of the activated set since the slope of the set size function was steeper for Lo span subjects than for Hi span subjects. The results of Exp. 1 are shown in the figure below. Clearly, Hi and Lo span subjects differ in slopes suggesting that they differ in search time for primary memory. Equally clear, however, is the fact that the difference between the 0 second slope function and the 1 second slope function is no greater for Lo span than Hi span subjects. This suggests that the time to retrieve a set into active memory does not differ for Hi and Lo span subjects. That difference is not any greater for set size 8 than for set size 4 which suggests that the time to activate a set does not depend on the size of that set. The results of Exp. 2, with words as items and set sizes up to 12 showed the same pattern.

Experiments 3 & 4 used sets with no overlap in membership. In both experiments, the results look most like those in Panel D in the first figure.

There was no WM difference in the retrieval time estimates for either active memory or inactive memory.

These 4 studies show that working memory capacity is not relevant to retrieval from memory unless there is a degree of interference or response competition involved in the task. We argued that, when each item was a member of 2 sets, the set cue activated the association to all items in that set and the item activated the association to both set cues. This led to a level of interference or response competition. Further, we argued that the Hi span subjects were able to inhibit the association between the item and the irrlevant set cue. However, the low span subjects, because of lower attentional resources, were not able to inhibit the link to the irrelevant set cue and thus were forced to do a full serial search of each set much like Sternberg proposed in 1966. In Experiments 3 & 4, in which there was no overlap in set membership, there was no difference between Hi and Lo span subjects in retrieval from primary or secondary memory.

It was primarily as a result of this series of studies that I modified my views about the mechanisms responsible for individual differences in working memory capacity. It became clear to me that high and low span subjects did not differ in automatic spreading activation. Differences in high and low span subjects were only demonstrated in these studies under conditions that likely forced controlled effortful attention. Further, the fact that high span subjects were unaffected by the interference manipulation suggests that they were able

to use their attentional capacity to suppress the inappropriate links in the interference conditions. By this view, to which I still subscribe today, the individual differences on putative measures of working memory that important to higher level cognition reflect individual variation in the ability to used sustained, controlled attention to maintain and/or suppress the activation of knowledge units. By this logic, the differences are not in 'working memory' per se but in the controlled attentional processes necessary to maintain and/or suppress representations in working memory. The new thinking fits nicely with Baddeley's view of the central executive (Baddeley, 1996), Shallice's view of the supervisory attentional system (Shallice & Burgess, 1995) and Moscovitch's view of 'working with memory' (Moscovitch, 1992).

(2) What is the relationship between the constructs of Short-term memory and Working memory? This study was directed at answering the question of whether STM and WM are the same, similar or different constructs. Do traditional STM tasks like word span and immediate free recall reflect the same construct as WM tasks like the reading and operation spans?

This study was conducted over the last 18 months and is still in the data analysis stage. A large scale factor analytic study investigated the relationships between measures of working memory, traditional measures of short-term memory, standardized measures of fluid general intelligence, and the verbal and quantitative Scholastic Aptitude Tests.

Each of 133 subjects were tested individually on a battery of tasks and tests in 3 sessions. The tasks and tests are listed below:

Operation Word Span (OSPAN): Subjects were presented with a series of math-word combinations such as "Is (6 x 1) - 1 = 11? DOG" which they read aloud. The subject's task was to solve the math problem (by deciding if the given answer was correct or not) while remembering the unrelated words. After 2-6 math-word combinations, subjects were given a recall cue (???) and were asked to recall the words in their correct order. Recall was scored as correct only if the words were recalled in their correct serial order.

Reading Span (RSPAN): This task is very similar methodologically to OSPAN, with one important difference. In RSPAN, subjects were presented with *sentences*, followed by unrelated words (e.g., The name of the USC mascot is Cocky. HOUSE) all of which they read aloud. Following word recall, subjects were given comprehension questions to make sure they were paying attention to the sentences. Word recall was scored as correct only if the words were recalled in their correct serial order.

Counting Span (CSPAN): In this task, subjects were presented with displays which contained dark blue circles, light blue circles and dark blue squares. During each display, subjects counted the number of dark blue circles. It was assumed that, following Triesman and Gelade (1988) that counting would be a controlled activity under these conditions. After 2-8 displays, subjects were given a cue (???) which indicated that they had to recall

the digit reflecting the number of dark blue circles from each previous display. Recall was scored as correct only when the number of dark blue circles from each display was recalled in the correct order. For example, if the number of dark blue circles on trial n was 1, the number on trial n + 1 was 6 and the number on trial n + 2 was 4, the correct recall would be 1, 6, 4.

Keeping Track (KTRACK): In this task, subjects were presented with 15 words on each trial, and were asked to recall the last exemplar of 1-6 categories. The critical categories were presented to the subject before and during word presentation. For example, if the categories ANIMALS and COLORS were presented before the list, the only words the subject had to recall were the *last* exemplar from each category (each category could have 1-5 exemplars per trial). Order of recall was not considered when scoring KTRACK data.

ABCD: In this task taken from the Kyllonen and Christal CAM4 battery, subjects were presented with 3 propositions describing the relative positions of 4 objects (e.g., The furniture is to the left of the animals; The dog is to the left of the cat; The table is to the right of the chair). Each proposition was presented for 3 seconds. Following the offset of the final proposition, 8 alternatives were presented to the subject (e.g., dog cat chair table). The subject's task was to choose the alternative that is consistent with all three descriptions. ABCD is scored as percentage correct.

Continuous Opposites (CONTOP): In this task also taken from the CAM4 battery, subjects were presented with 3 - 8 words. The words were presented on the monitor, and appear in red or white type. If a word was presented in white, subjects were supposed to remember that word. If a word was presented in red, they were supposed to remember the opposite of that word. When given the recall cue, subjects recalled the last three words (or their opposites) that were presented to them.

Immediate Free Recall (IFR): In this task, subjects were presented with 12 words on each trial. The words were presented visually, but the subjects read them aloud. When given the recall cue (???), subjects were asked to write down as many words as they could remember. Two scores were derived from these data. Immediate free recall primary memory (IFRPM) were words recalled with 7 or fewer intervening words between presentation and recall were scored as IFRPM. The IFRPM score is the average number of these words. Immediate free recall secondary memory (IFRSM) were words recalled with 8 or more intervening words between presentation and recall were scored as IFRSM. The IFRSM score is the average number of these words.

Random Generation: In this task modeled after Baddeley's work (1996), subjects were asked to randomly generate numbers (1-9) at the rate of 1 number every second. The task was performed in the following way: subjects heard a tone (from a tape recorder) at the rate of one tone per second. They were instructed to randomly generate a single digit for each tone. As the

subject said the digits, an experimenter keyed the digits into the computer for later analysis. The random generation was a measure of the degree of randomness in each subject's output.

Forward Span Dissimilar (FSPAND): In this task, 2 - 7 words were presented at the rate of one word per second. Subject's read aloud each word as it was presented. Following the final word, a recall cue (???) was given to the subject, at which point they recalled the words from the previous trial. Recall was scored correct only if the words were recalled in the correct serial order.

Forward Span Similar (FSPANS): This task was nearly identical to FSPAND with one exception: In FSPANS, on each trial, all the words rhymed (e.g., DOG, BOG, HOG).

Backward Span (BSPAN): This task was also similar to FSPAND with one exception. In BSPAN, subjects were asked to recall the words in the reverse order that they were presented. For example, if the subject was presented with DOG, CHAIR, HOUSE, the correct recall would be HOUSE, CHAIR, DOG.

Cattell Culture Fair Test (Cattell): This standardized test is a visual/spatial problem solving task that has been shown to be an important non-verbal measure of general fluid intelligence (Duncan, Emslie, Williams, Johnson and Freer, 1996).

Raven's Progressive Matrices (Raven's): This standardized test is commonly used visual/spatial problem solving task that has been shown to be

an important diagnostic for general fluid intelligence (Snow, Kyllonen, Marshalek, 1984; Ackerman, 1986).

Verbal and Quantitative Scholastic Aptitude Tests (VSAT and QSAT): We have used these highly standardized tests, particularly the VSAT, to reflect general verbal comprehension skills. It is likely that the two tests taken together also reflect some fluid as well as crystalized intelligence components of intelligence.

Preliminary analyses of the data have shown the following. First, the memory measures were analyzed separately from the standardized tests. A confirmatory factor analysis showed that a two factor solution was a significantly better fit than a one factor model. The two factors were: a STM factor consisting of the forward span dissimilar, forward span similar and backward span tasks and a WM factor consisting of the operation span, reading span, counting span, keeping track, immediate recall secondary memory component, ABCD and continuous opposite tasks. An analysis using the weighted factor scores showed that WM and g (a factor composed of Cattell and Raven's) were related (r=.5) even when the STM factor was partialled out of the relationship. While the simple STM, g relationship was significant, it was negligible when the WM factor score was partialled out (r=.10).

An analysis was also done with the factor scores and VSAT. This anaysis gave a different pattern of results. Both the WM, g relationship and the STM, g relationship were significant when partialling out the other factor.

This suggests that the two factors contribute significant unique variance to VSAT.

Another finding of note is what did not fit with the factor analyses. The immediate free recall-primary memory and random generation tasks simply would not comfortably fit with either factor. The random generation in particular wanted to go off by itself from the other measures.

Another non-finding of note from these analyses had to do with the articulatory loop. We included the forward spans similar and dissimlar to attempt to get some index of individual differences in the loop. Similar to a recent paper by Logie, et al (1996), we found that the difference between the similar and dissimilar conditions for each subjects, known as the similarity effect, was unreliable with 20/133 subjects showing no or a negative effect. There was no correlation between the difference score and any of the higher level measures.

These results are quite striking in showing that the traditional measures of short-term memory, even though they may predict some higher level measures of verbal comprehension such as the VSAT, are not equivalent to the newer complex working memory measures such as the operation and reading-span. It should also be pointed out that the counting span, unlike any other measure in this study, required the subject to remember a list of digits. Yet this task loaded about the same on the WM factor as did the OSPAN and RSPAN. The backward span task has been described in the developmental

liturature (Case, 1985) as a M-space or WM task but it loaded predominantly with the STM factor NOT the WM factor.

We still have several other analyses to do on these data before the picture is complete. For example, we will do some simple structural modeling. However, those analyses should not tell us much more than the partial correlation analyses already performed. At that time we plan to write up the results of the study for publication and we are currently aiming for Journal of Experimental Psychology: General.

(3) Are the important differences in working memory reflected by the complex span tasks a result of individual differences in activation or inhibition? While general capacity theory clearly assume individual differences in working memory occur as a result of differences in available activation, one alternative argument can be made that these effects occur as a result of individual differences in inhibition. Another view is that maintaining and suppressing activation both require controlled attention and that individual differences in controlled attention cause the differences we observed on measures of working memory capacity.

As previously described, the Conway and Engle (1994) clearly suggested that individual differences in working memory would only be important to a task like speeded retrieval if the conditions provided a level of interference or response competition. In addition, we have now done several sets of studies directed at tasks thought to directly reflect cognitive inhibition. In

severalpapers already published and several others still in the publication pipeline, my lab has argued that individual differences in working memory capacity will only be important to controlled retrieval and will not be important under conditions that allow retrieval based on automatic spreading activation. Further, we have argued that attentional resources, the basis for what we refer to as working memory capacity, is necessary for inhibition of irrelevant information.

In a paper published in in *Psychological Science* (Engle, et al, 1995), we studied the effects of mental work load on the negative priming effect. That effect occurs when subjects are required to name one of two letters presented simultaneously and overlapping. For example, if a red and a green letter are presented at the same time, the subject would always be asked to name the red one as rapidly and accurately as possible. So, if a red A and a green B were presented on trial n, the subject would be required to name the A. Tipper and Cranston (1985) argued that, in order to attend to the A, the subject must inhibit the B. If that is so and, on trial n+1, the subject sees a red B, it should take more time to name the B on that trial because it had been inhibited on the previous trial. That is exactly what is found and this effect is called the negative priming effect.

We reasoned that inhibition would require attentional resources and, if so, requiring the subject to do a secondary task that was attention demanding while they did the naming task might reduce the magnitude of the negative

priming effect. We had subjects naming red letters and ignoring the green letters. Interspersed between the naming trials were words that the subject was read silently and, at some later time, they would see a question mark which signaled the recall of the words in the correct order. On the first letter naming trial after a recall, we reasoned that the subject was operating under a 0 load, when the letter was named after the first word was presented, the subjects was operating under a load of 1 and so on up to a load of 4 words. The results showed that, at 0 load, there was a sizable negative interference, i.e., the letter was named more slowly if it had been rejected on the previous trial. As load increased, however, the negative priming effect was reduced and actually became positive by load 3. We have now completed three studies following up that finding. The first study was essentially a direct replication which confirmed the published findings. The other two studies extended the findings. In both we used the letter naming task as our index of negative priming. In the first study, the attention demanding task was a word recognition task. The subject saw a word prior to each trial and, at the end of a block, the subject pressed a button to indicate whether a word one of the 4 words just shown or was not one of the 4 words. The second study was identical to the first except instead of being shown words to remember, the subject was shown abstract polygons and, at the end of the block, another polygon was shown for recognition. The findings for the two studies were

remarkably similar. With 75 subjects in the first study and 80 in the second, there was a significant negative priming effect in the 0 load condition but the effect was eliminated with a load of 1-4 items, either words or polygons. This shows that the negative priming effect, and presumably the underlying construct of inhibition, is vulnerable to the effects of mental workload, i.e., it is difficult to inhibit and block distracting information under load. Both studies also showed an effect of individual differences in working memory capacity. Hi spans showed the significant negative priming characteristic of the sample as a whole but Lo spans did not show a negative priming effect even at load 0. The paper based on the last two studies was recently submitted to Perception and Psychophysics.

These studies were instrumental in supporting the argument that central executive or controlled attention capacity was important in cognitive suppression and high working memory subjects were better at suppressing the activation of a knowledge unit than were low working memory subjects. However, there is some controversey about the causes of the negative priming effect. Therefore, we hoped to test a more direct measure of suppression ability. In two dissertation studies by Rosen, we had high and low working memory subjects perform an A-B, A-C, A-B paired associate task. The first list (A-B) was composed of 12 highly associated compound word pairs such as BIRD-BATH, KNEE-PAD, etc. These were learned to a criterion of 4 correct recalls for each pair. The next pair was composed of the same cue word with a

less associated word, for example, BIRD-DAWN. Again, the pairs were learned to 4 correct recalls for each item. The third list was a repeat of list 1, BIRD-BATH. The first experiment strongly emphasized accuracy in the instruction and we measured the vocal response latency to say the response, e.g., BATH when the subjects was shown the cue word, e.g., BIRD. It was assummed that the accuracy emphasis would make the retrieval time a more sensitive measure of suppression. Postman, Stark & Fraser (1968) have argued that suppression of list 1 responses occurrs during the learning of list 2. If that is correct, we should see slowed retrieval on the first trial of list 3. The queston is whether this would be the same for high and low working memory subjects. Our theory would suggest that high span subjects would have the attentional resources to do the suppression during the learning of list 2 but that low spans might not. The retrieval time to retrieve BATH to BIRD on list 3 was slowed by 160 msec for high span interference group compared to the high span control group. The low spans were significantly faster to retrieve the response word than their control group. Further, the high span interference subjects were even slower to retrieve BATH to BIRD on the first trial of list 3 than they were on the first trial of list1. The within subject comparison showed a slowing of 140 msec for the high span subjects. The within list comparison for the low spans showed no differences from list 1 to list 3.

The second study emphasized speeded responding through instructions and a response deadline of 1350 msec. We assummed these procedures would

increase the sensitivity of the probability of correct and, in particular, the liklihood of making intrusions. It was thought that, if high span subjects are better at suppressing the distracting information from the first list during learning of the second list, under the speeded conditions, low spans would make more intrusions. This was exactly what we found. There were more than twice as many intrusions for the low span subjects during the learning of list 2.

To summarize, my thinking about individual differences in working memory capacity is now that high and low working memory subjects do NOT differ in automatic spreading activation. Based on the studies above, I have concluded that differences on the complex measures of working memory such as operation and reading span reflect the ability of subjects to use controlled attention to maintain knowledge units necessary for the task at hand and to suppress the activation of knowledge units irrelevant or inappropriate or competing with the task at hand.

(4) What is the role of the phonological loop in individual differences in WM? There has been extensive work by Baddeley (1986) and others demonstrating the importance of phonological coding in certain types of STM tasks and that this coding plays a role in reading and other language oriented tasks. However, we do not know how this type of coding interacts with the type of individual differences studied in our lab.

I have already described the recently completed factor analysis which showed that the phonological similarity effect, i.e., the difference between recall

of similar and dissimilar lists, was unreliable and did not correlate with VSAT or the g measures.

Earlier, five experiments were conducted on this problem. I will present the conclusion from those 5 experiments and then describe the procedures that led to those conclusions. ***The phonological similarity effect does NOT occur when the lists are chosen from an unlimited pool of words, UNLESS, the words are spoken aloud at input. Even then, however, the effect is a quarter of the effect when the lists are chosen from a fixed set of items such that the words are used over and over again on each list.***

In each of 5 experiments we varied whether the lists items were chosen from a limited set of 7 items used over and over across lists or from a functionally unlimited set with no repetition of a word from list to list. We also varied whether the lists items were phonologically similar on each list or were dissimilar. Across experiments, we varied whether the words were read silently at input or were read aloud by the subject and whether recall was written or oral. In all experiments, if the lists were chosen from a limited set, there was a sizable phonological similarity effect regardless of input or output mode. In the unlimited condition, however, if input was silent, no phonological similarity effect was found regardless of mode of recall. If the words were articulated aloud at input, there was a small but significant effect of phonological similarity regardless of mode of recall. Even in this case, however, the

phonological similarity effect was a quarter of the size of the effect in the limited set condition.

This finding is very important because it casts great doubt on the generality of the type of coding referred to as the articulatory loop. The pattern of correlations with various measures of rehearsal rate suggests that subjects in the unlimited condition with silent visual presentation do use some type of speech based code but that it is different than the articulatory loop code.

(5) Is there a meaningful relationship between the size of chunks of knowledge in long-term memory and working memory capacity? We did not do the specific studies proposed under this question in the original proposal. However, this question was addressed obliquely through a series of studies on controlled retrieval in the fluency task.

General capacity theory predicts that differences between high and low span subjects would appear in the nature of retrieval in a category exemplar task like that used by Gruenewald and Lockhead (1980). They presented subjects with a category name and the subjects were asked to recall as many exemplars from the category as possible. Gruenewald and Lockhead found that recall was a scalloped function with bursts of exemplars of about 5 items followed by a pause then around 5 more items. Baddeley, et al (1984) showed that, while other types of retrieval were not affected by a concurrent task, performance in a category generataion task was hurt by a concurrent task. This suggested to us that, since controlled attention appears to be important in

the category generation task, there should be systematic differences between high and low working memory subjects. We might be able to use this task, sometimes referred to as a verbal fluency task, to study the role of working memory capacity on retrieval.

Rosen and Engle (in a paper now in revision to JEP:G) tested subjects in an experiment in which we simply asked them to recall as many exemplars of the category <u>animal</u> as possible within a 10 minute period. They were also instructed to avoid repeating any animals. The subjects were defined as high and low working-memory-capacity on the basis of the operations word span. We transcribed the specific words and the time at which each word occurred from audio and video tapes. Our original version of general capacity theory argued that high span subjects should be able to spread activation to more units per each retrieval attempt than low span subjects and, thus, the difference in recall should increase over time. While the recall for high span subjects was only slightly higher in the first minute of recall, the disparity grows greater over time.

Baddeley, et al (1984) found that retrieval in this task was hampered by a concurrent load suggesting that retrieval from natural categories is a controlled, effortful process. Therefore, a logical question is whether a load would differentially affect high and low WM capacity subjects. One obvious possibility is that, since low span subjects have smaller resource capacities anyway, a load would hurt their retrieval while the high span subjects would be

able to use their greater resources to overcome the effect of the work load. If that were the case, we should see the retrieval differences between high and low span subjects exaggerated under a concurrent load.

Another possibility, however, is that high and low span subjects rely on different strategies to perform this task. It is possible that high span subjects generate more words because they do the controlled, effortful search that Baddeley, et al, attributed to their subjects. Low span subjects, on the other hand, may use retrieval based on automatic spreading activation, in which case, they should be hurt less by a concurrent mental load than the high span subjects.

In the next study, Rosen and I had high and low span subjects genrerate animal exemplars under one of two conditions. In one condition, the subject generated animals while shadowing digits presented at a 1.5 second rate in consecutive corners of a computer monitor. The subject was to press a button on the keyboard as fast as possible whenever a third odd digit in a row occurred. This required the subject to keep a running set of 1-3 digits in working memory and thus constituted a memory load condition. The no load condition was identical to the previous experiment and thus constituted a replication.

The No Digit control groups replicated the results from the first experiment in showing greater generation of animal names for high span subjects. Performing the concurrent digit tracking task had no significant

impact on the low span subjects. Their recall function was nearly identical to the low span subjects who had no memory load and both were nearly identical to the low span subjects from the first experiment. The high span group that retrieved under load were significantly hampered in the number of animals they could generate but still generated significantly more words than the low span subjects. Thus, the attention-demanding concurrent task hurt the performance of the high span subjects but had no significant effect on the performance of the low span subjects. These findings support the idea that high span subjects use controlled, effortful search to perform the retrieval from natural categories while, for low span subjects, retrieval is a result of an automatic, effortless process.

Recall that subjects in these experiments were instructed to not repeat any words. Thus, the task required the subject to keep track of items they had generated and to not say those words again. Keeping track of previously recalled items is, itself, a drain on attentional resources. In the next study we wanted to specifically manipulate this feature by giving subjects a pre-load of items that they were to NOT recall.

We had high and low WM capacity subjects learn a list of 12 words until they could recall the list perfectly. Half the subjects learned a list of high frequency ***animal*** names (e.g., bird, cat, cow, and dog), this was the related condition. The other half of the subjects were in the unrelated condition and learned a list of 12 high frequency ***building parts*** (wall, door, window, etc).

After the list was learned, subjects were instructed to name as many animals as they could think of in 10 minutes but to NOT recall any of those words learned in the previous list and to NOT repeat any words.

We had anticipated that recall would be hurt most for the the related condition, and, after the findings of the previous experiment, reasoned that the high span subjects might be hurt more than the low span subjects. We had also anticipated, however, that the unrelated condition should serve as a control group and be no different than the control group from Experiment 2. After all, it made no sense that telling the subject to not recall building parts while they were trying to recall animal names should in any way interfer with the retrieval of animal names.

While recall was differentially hurt for the high span subjects, the decrement was nearly as great for the unrelated as well as for the related condition. Both were significantly lower than the control condition from the previous study. Learning and\or being told to not recall the items from the learned list hurt retrieval for the high span subjects regardless of whether the list was composed of items from the animal category.

As with the concurrent load condition, low span subjects were unaffected by either pre-load condition. Low span retrieval functions from all three experiments were nearly coincident regardless of load condition.

These studies showed that individual differences on the working memory task correspond to individual differences in a free recall task. Further, either a

concurrent memory load or a pre-load causes a decrement in recall for high span subjects but has no impact on retrieval for low span subjects. The category retrieved from in these experiments was animals and the category is large enough that it is unlikely that performance would be limited by differential knowledge about animals or differential vocabulary knowledge for animal names.

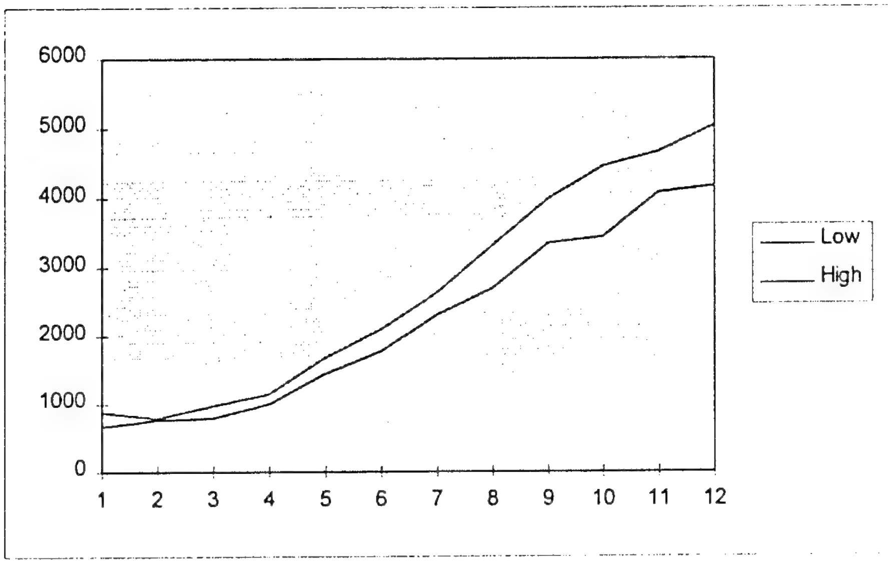
Miscellaneous Studies.

One of the questions posed by this research was to what extent the processing component of the complex working memory span tasks accounts for the variance shared with the higher level cognition tasks. So, for example, in the operation word span task, does the difficulty of the processing component determine the correlation between the Ospan and reading comprehension? Conway and Engle (1996) did a study in which subjects were pretested on a broad range of arithmetic operations so that we could chose operations for the operation-word span task such that subjects would be equated at 92%, 85%, and 75% accurate on the operation portion of the operation span task. These three operation span measures and the form of the operation span task we typically use which presents all subjects with the same set of operations were all correlated at about the same level with reading comprehension. The processing theory (c.f., Daneman & Tardiff, 1992) predicts that the operation spans with difficulty equated should eliminate the correlation between operation span and reading comprehension. However, the correlation between

operation span and reading comprehension was nearly identical at all three levels of difficulty to the operation span with difficulty not equated across subjects. This finding seems impossible to explain by any processing oriented theory.

Another study we completed this year used the subitizing task to test our view that working memory capacity would be important in tasks that are controlled nature but not for tasks that can be done with automatic processing. The subitizing task is simply to have subjects count the number of objects on a screen. When counting time is plotted as a function of the number of objects counted, two different functions are observed. The slope over 1-4 objects is relatively flat. However, from 5-12 objects shows a much steeper function. The most popular interpretation is that 1-4 objects are not counted per se but simply recognized as a gestalt. However, beyond 4 objects requires controlled counting.

We did a study in which high and low working memory capacity subjects performed 760 trials in a counting task and orally reported the number of objects. The dependent variable was the vocal response time. As seen in the figure on the next page, there was no slope difference between high and low span subjects when counting 1-4 objects. However, from 5-12 the low span subjects were much slower per object counted. Our interpretation was that the low spans were slower to count because controlled attention was necessary to do this task.



Conclusions based on the funded work

The work funded by this grant has been incredibly successful in discovering some underlying principles about individual differences in working memory. I started the work with the view that working memory differences were a result of differences in activation available to the information processing system. If, however, by activation we mean the same thing as authors such as Posner and Snyder (1975) mean by automatic spreading activation, then that view was clearly wrong. High and low working memory subjects do not perform differently on tasks that can be performed using automatic activation. However, if the task allows, encourages, or forces controlled attention for processing then individual differences in working memory capacity will manifest themselves. This new view brings my thinking in line with Baddeley's thinking about the central executive. That view sees the important individual differences in working memory as due to controlled attention, not a memory

representation per se. It is similar to the views of Shallice (c.f., Shallice & Burgess, 1993) on the supervisor attentional system and Moscovitch (1992) on working-with-memory. By this view, the mechanism underlying individual differences in working memory capacity is a central, domain-free attentional system, associated with the frontal lobes. The system is important in novel tasks that are non-proceduralized, for maintaining information active for intermediate processing and for suppressing distracting or inappropriate information. The relationship between controlled attention and suppression is a very new idea and our work on the negative priming effect and on the suppression of responses in a paired associate task strongly support this view.

The Air Force has received good value for its money in this research and the research proposed in the future will further add to our knowledge about the mechanisms and real-world importance of this system. To quote from a recent paper of Baddeley's (1996) "Engle's results ask some searching questions about three of the major phenomena of cognitive psychology, namely the Sternberg effect, the fan effect and the Daneman and Carpenter measure of working memory span. As such they have substantial implications for understanding the role of working memory in retrieval from long-term memory."

References

Ackerman, P. (1986). Individual differences in information processing: An investigation of intellectual abilities and task performance. Intelligence, 10, 101-139.

Anderson, J. R. (1983a). The architecture of cognition. Cambridge, MA: Harvard University Press.

Atkinson, R. C., & Shiffrin, R. M. (1968). Human memory: A proposed system and its control processes. In K. W. Spence & J. T. Spence (Eds.), The psychology of learning and motivation (Vol 2), New York: Academic Press.

Baddeley, A. D. (1996). The central executive. Quarterly Journal of Experimental Psychology.

Baddeley, A. D., Lewis, V., Eldridge, M., & Thomson, N. (1984). Attention and retrieval from long term memory. Journal of Experimental Psychology: General, 113, 518-540.

Broadbent, D. E. (1975). The magic number seven after fifteen years. In A. Kennedy & A. Wilkes (Eds.), Studies in long-term memory. New York: Wiley.

Cowan, N. (1988). Evolving conceptions of memory storage, selective attention, and their mutual constraints within the human information-processing system. Psychological Bulletin, 104, 163-191.

Cantor, J. & Engle, R. W. (1993). Working memory capacity as long term memory activation: An individual differences approach. Journal of

Experimental Psychology: Learning, Memory, and Cognition, 19, 1101-1114.

Cantor, J., Engle, R. W., & Hamilton, G. (1991). Short-term memory, working memory, and verbal abilities: How do they relate? Intelligence, 15, 229-246.

Conway, A. R. A. and Engle, R. W. (1994). Working memory and retrieval: A resource-dependent inhibition model. Journal of Experimental Psychology: General, 123, 354-373.

Daneman, M. & Carpenter, P. A. (1980). Individual differences in working memory and reading. Journal of Verbal Learning and Verbal Behavior, 19, 450-466.

Daneman, M. & Carpenter, P. A. (1983). Individual differences in integrating information between and within sentences. Journal of Experimental Psychology: Learning, Memory and Cognition, 9, 561-583.

Daneman, M. & Green, I. (1986). Individual differences in comprehending and producing words in context. Journal of Memory and Language, 25, 1-18.

Daneman, M. & Tardiff, T. (1987). Working memory and reading skill reexamined. In M. Coltheart (Ed.), Attention and Performance XII. London: Erlbaum.Engle, R. W. (1996). Working memory and retrieval: An inhibition-resource approach. In Working memory. J. Richardson (Ed.), Oxford University Press.

Duncan, J. Emslie, H., Williams, P., Johnson, R., & Freer, C. (1996). Intelligence and the frontal lobe: The organization of goal-directed behavior. Cognitive Psychology, 30, 257-303.

Engle, R. W., Cantor, J., & Carullo, J. J. (1992). Individual differences in working memory and comprehension: A test of four hypotheses. Journal of Experimental Psychology: Learning, Memory, & Cognition, 18, 972-992.

Engle, R. W., Carullo, J. J., & Collins, K. W. (1991). Individual differences in the role of working memory in comprehension and following directions in children. Journal of Educational Research, 84, 253-262.

Engle, R. W., Conway, A. R. A., Tuholski, S. W., and Shisler, R. J. (1995). A resource account of inhibition. Psychological Science, 6, 122-125.

Engle, R. W., Nations, J. K., & Cantor, J. (1990). Is working memory capacity just another name for word knowledge? Journal of Educational Psychology, 82, 799-804.

Ericsson, K. A. & Staszewski, J. (1989). Skilled memory and expertise: Mechanisms of exceptional performance. In D. Klahr & K. Kotovsky (Eds.), Complex information processing: The impact of Herbert A. Simon. Hillsdale, NJ: Erlbaum.

Glass, A. L. (1984). Effect of memory set in reaction time. In J. R. Anderson and S. M. Kosslyn (Eds.), Tutorials in learning and memory: Essays in honor of Gordon Bower. San Francisco: Freeman.

Greunewald, P. J. & Lockhead, G. R. (1980). The free recall of category examples. Journal of Experimental Psychology: Human Learning and Memory, 6, 225-240.

Just, M. A., & Carpenter, P. A. (1992). A capacity theory of comprehension: Individual differences in working memory. Psychological Review, 99, 122-149.

Kyllonen, P. C. & Christal, R. E. (1990). Reasoning ability is (little more than) working-memory capacity. Intelligence, 14, 389-433.

Kyllonen, P. C. & Stephens, D. L. (1990). Cognitive abilities as determinants of success in acquiring logic skill. Learning and individual differences, 2, 129-160.

La Pointe L. B., & Engle, R. W. (1990). Simple and complex word spans as measures of working memory capacity. Journal of Experimental Psychology: Learning, Memory and Cognition, 16, 1118-1133.

LaPointe, L. B. and Engle, R. W. (1990). Simple and comples word spans as measures of working memory capacity. Journal of Experimental Psychology: Learning, Memory, and Cognition, 16, 1118-1133.

Moscovitch, M. (1992). Memory and working-with-memory: A component process model based on modules and central systems. Journal of Cognitive Neuroscience, 4, 257-267.

Ormrod, J. E. & Cochran, K. F. (1988). Relationship of verbal ability and working memory to spelling achievement and learning to spell. Reading research and instruction, 28, 33-43.

Postman, L., Stark, K., & Fraser, L. (1968). Temporal changes in interfernce. Journal of Verbal Learning and Verbal Behavior, 7, 672-694.

Tipper, S. P., and Cranston, M. (1985). Selective attention and priming: Inhibitiory and facilitatory effects of ignored primes. Quarterly Journal of Experimental Psychology, 37A, 581-611.

Turner, M. & Engle, R. W. (1989). Working memory: An individual differences approach. Journal of Memory and Language, 28, 127-154.

Schneider, W. & Detweiler, M. (1987). A connectionist/control architecture for working memory. In G. H. Bower (Ed.), The psychology of learning and motivation (Vol. 21). New York: Academic Press.

Shallice, T. & Burgess, P. (1993). Supervisory control of action and thought selection. In Attention: Selection, awareness, and control. A.Baddeley & L. Weiskrantz (Eds). London: Oxford University Press.

Snow, R.E., Kyllonen, P.C., & Marshalek, B. (1984). The topography of ability and learning correlations. In Advances in the psychology of human intelligence. R.J. Sternberg (Ed.). NY: LEA Publishing.

Waugh, N. C. & Norman, D. A. (1965). Primary memory. Psychological Review, 72, 89-104.

Scientific papers resulting from this work.

Articles:

1. Conway, A. R. A. & Engle, R. W. (1994). Working memory and retrieval: A resource-dependent inhibition model. *Journal of Experimental Psychology: General, 124*, 354-373.

2. Engle, R.W., Conway, A.R.A., Tuholski, S.W., & Shisler, R.J. (1995). A resource account of inhibition. *Psychological Science, 6*, 122-125.

3. Conway, A. R. A. & Engle, R. W. (1996). Individual differences in working memory capacity: More evidence for a general capacity theory. (In press, *Memory*).

4. Tuholski, S.W. & Engle, R.W. Mental models: Now you see them, now you don't. (submitted to Memory and Cognition.)

5. Shisler, R.J., Conway, A.R.A., Tuholski, S.W., & Engle, R.W. Attentional resources and inhibition: The effects of mental load on negative priming. (Submitted to Perception and Psychophysics.)

6. Rosen, V. & Engle, R.W. The role of working memory capcity in retrieval. (Submitted to Journal of Experimental Psychology: General).

7. Rosen, V. & Engle, R. W. Individual differences in working memory capacity and resistence to interference in a paired associate task. (Submitted to Journal of Experimental Psychology: Learning, Memory and Cognition).

Chapters:

1. Engle, R. W. (1995). Memory. In Encyclopedia of human intelligence. R. J. Sternberg (Ed). NY:Macmillan.

2. Engle, R. W. (1996). Working memory and retrieval: An inhibition-resource Approach. In J. Richardson (Ed). Working memory. London: Oxford University Press.

Theses and dissertations completed on this grant.

Conway, A.R.A. Retrieval and working memory. MA thesis, 1993.

Tuholski, S. W. Individual differences in the fan efffect: The effect of interference. MA thesis, 1994.

Shisler, R.J. Individual differences in working memory capacity and the Stroop test. MA thesis, 1996.

Skedsvold, P. R. Understanding the impact of working memory capacity on impression formation. Ph.D. Dissertation, 1993.

Conway, A.R.A. A test of the episodic retrieval theory of negative priming. Ph.D. Dissertation, 1996.

Rosen, V. M. Individual differences in working memory capacity and resistance to interference in a paired associate task. Ph.D. Dissertation, 1996.

Personnel supported

Randall W. Engle - faculty member
Andrew Conway - graduate student
Steven Tuholski - graduate student
Rebecca Shisler - graduate student